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Influence of material choice, renovation rate, and electricity grid to achieve a Paris Agreement-compatible building stock: A Portuguese case study

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A R T I C L E   I N F O

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A B S T R A C T

The thermal retrofit of buildings plays a key role to limit global warming. However, the spatial and temporal dynamics of urban-scale renovation are not well understood. This paper proposes a new methodology that is based on a bottom-up building stock model. It links dynamic Material Flow Analysis with dynamic Life Cycle Assessment to include the temporal dynamics of emissions and renovation activity, and the spatial dynamics of the building stock. Alternative renovation scenarios for a Lisbon neighborhood are analyzed over the next 100 years. Thee scenarios include renovation rates, electricity grid transformation and material choice: Conventional renovation systems are compared to bio-based systems (using cork, wood and straw). A need-based prioritization of poorly insulated buildings is suggested and the effect of different energy grid transitions analyzed. The results show that bio-based systems, especially made with fast-rotation biomass, are beneficial regarding radiative forcing. The straw- and wood-based system ("TES"), combined with an increased renovation rate, result in a cumulative radiative forcing of $-45.4 * 10^{-8}$ kW/m^2 for embodied impacts in 2050, compared to $3.5* 10^{-8}$ kW/m^2 with a conventional system and a business-as-usual renovation rate. A fast and radical transition of the energy grid is crucial to meet the carbon budget to limit global warming to 2 °C.

1. Introduction

The Paris Agreement from 2015 [1] was an international recognition of climate change and created an urgency to limit global warming, if possible to 1.5 °C, or as of 2019, more realistically to 2 °C [2]. After years of debating, governments are finally taking action: the European Green Deal, decided upon in 2019, sets the ambitious goal of attaining carbon neutrality by 2050 [3]. Since currently circa 75% of the European building stock is estimated to be energy-inefficient [4], buildings are said to play a key role in achieving this goal. Additionally, there is a growing trend of people working from home, which is accelerated by the global Corona health crisis [5]. This trend intensifies the need for energy efficient residential buildings (hereafter referred to as dwellings). While the global population is rapidly increasing, population growth in Europe is stagnating [6]. Therefore, renovation of dwellings, instead of new construction, is destined to become the main driver of building stock adaptation in Europe [7,8].

Even though the opportunity for renovating buildings seems to be challenging and complex, some scholars warn of the lock-in effect [9] and that any renovation needs to be ambitious, otherwise more emissions will be emitted for a relatively small improvement of energy efficiency. Moreover, coordinated and strategic actions are required for a radical transformation of building stocks [10]. However, there is no clear consensus on what "ambitious" renovation is, and which "strategic actions" for building stock transformation actually have climate mitigating leverage. Building passports, for example, want to promote deep renovation. However, there is a lack of a common definition across EU countries for this certification scheme [11].

While until some years ago, policy and research focused on the impacts arising during the operation of a building [12], it was shown that embodied impacts, related to the production and construction processes,

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Abbreviations

BAU	Business as usual
DLCA	Dynamic Life Cycle Assessment
EoL	End of Life
EPS	Expanded Polystyrene
ETICS	External Insulation Composite System
FU	Functional unit
GHG	Greenhouse Gas
GIS	Geoinformation system
GWI_{inst}	Instantaneous radiative forcing
GWI_{cum}	Cumulative radiative forcing
GWP	Global Warming Potential
GWP_{dyn}	relative life cycle cumulative impact over the cumulative impact of a 1 kg CO_2 pulse emission at time zero
ICB	Insulation Cork Board
LC	Life Cycle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MFA	Material Flow Analysis
SI	Supplementary Information
TES	Timber based element system with different options for thermal insulation (in this paper:straw) for improving energy efficiency of the building envelope

are increasing in relative terms over the life cycle since an increased energy efficiency of buildings reduces the operational impacts [13], and in total terms in new and advanced residential construction [14]. Therefore, the choice of insulation material and renovation system seems crucial. One of the suggested possible "strategic actions" that is related to materials is the use of carbon capture and storage technologies [15]: by using bio-based materials in buildings, carbon is temporarily stored, which at the end of life of the building or construction product is released as CO_2 back to the atmosphere. Bio-based insulation materials provide a similar thermal performance to conventional materials. Assuming a sustainable supply of biomass, the biomass used in construction is regenerated in new plants, again sequestering carbon in the natural system. Therefore, the biogenic carbon cycle is usually considered neutral. However, Levasseur et al. [16,17] showed that the carbon cycle is in fact not neutral. They promoted the use of Dynamic Life Cycle Assessment (DLCA) to account for the timing of carbon uptake and Greenhouse Gas (GHG) emissions for an accurate analysis of impact results, which is especially important for bio-based products and systems. This was confirmed by the recent review of DLCA studies by Beloin-Saint-Pierre et al. [18]. Moreover, Levasseur et al. [16] developed the *DynCO$_2$* calculation tool [19], which provides results for instantaneous radiative forcing (GWI_{inst}) and cumulative radiative forcing (GWI_{cum}) in W/m^2. The latter measures long-term effects on the terrestrial radiative equilibrium [8] whose imbalance changes global temperatures [20]. Additionally, the relative impact expressed in CO_2 eq. (GWP_{dyn}) is calculated, which refers to the Life Cycle (LC) cumulative impact over the cumulative impact of a 1 kg CO_2 pulse emission at time zero. In this way, the results are transformed into the same units as used by conventional LCA through Global Warming Potential (GWP), but considering the timing of the emissions [19]. When considering the timing of emissions and carbon uptake, the supposition that carbon-neutral is equal to climate-neutral needs to be questioned [21]. Only when the carbon uptake of regenerated biomass in nature, which is induced by the use of biomass in construction, fully compensates the embodied (and the operational impacts) in terms of GWI_{cum}, then the building (stock) is climate-neutral [22].

Pittau et al. [22] analyzed bio-based wall systems with DLCA for a functional unit (FU) of 1 m^2 of wall during 60 years lifetime. The authors found that specifically fast-growing materials like hemp or straw, thanks to their fast rotation periods, could decrease the carbon footprint of buildings. The same authors followed up with a study [8] of the future renovation of the European dwelling stock to analyze the potential of extensively storing carbon in external walls. In accordance with EN 15804:2012 [23], they considered the Life Cycle (LC) product stage (A1-A5), the replacement of renovation elements (B4), the end of life (EoL) (C1–C4), and the carbon uptake related to the use of biomass, while the operational energy use (B6) was neglected. By applying DLCA, they found that straw is particularly sensitive to the EoL scenario but can lead to net negative cumulative radiative forcing after only three years. Pittau et al. [8] analyzed bio-based retrofit of the EU housing stock with DLCA and employed a top-down building stock model based on statistical data for different geoclusters. This model led to generalized results across geoclusters. For an improved material choice, the urban scale can be recommended and the dynamics of renovation could be better captured with a bottom-up model [24]. García-Pérez et al. [25], for example, used a bottom-up building stock model of Barcelona based on geoinformation systems (GIS) to compare different thermal insulation materials, including insulation cork board (ICB). By georeferencing, their results could be traced back to the individual building [26]. They used conventional (static) LCA and found that there are significant differences between different types of buildings and urban morphologies.

There is a lack of studies of building stock renovation that include the temporal dynamics of emissions and the spatial dynamics of the building stock. Only when considering these dynamics, the potential of achieving climate neutrality can be estimated. Moreover, the dissection of dynamic inputs allows a better understanding of their leverage for the reduction of impacts to comply with the 2 °C target of the Paris agreement, and therefore to define informed strategies.

2. Research question

The research question of this paper is as follows: How do different dynamics, such as (bio-based) material choice, annual renovation rate, building stock characteristics and energy supply, contribute to reduce emissions of urban-scale renovation? More specifically, considering the different dynamics, which challenges need to be overcome to achieve a climate neutral building stocks by 2050?

For this purpose, a new methodology is proposed that links dynamic LCA and dynamic material flow analysis (MFA) with a bottom-up archetype-based approach.

3. Method

3.1. Linking dynamic LCA and MFA

A hybrid methodology is proposed, which is presented in Fig. 1. It entails, firstly, a MFA to estimate the renovation-induced material requirements over time. For the building inventory, the actual building footprints are collected from Monteiro's [27] geodatabase that categorize buildings into archetypes. The total external façade area to be renovated was calculated in GIS considering the actual perimeter of the building's footprint multiplied with the height of the assigned archetype, and subtracting walls with neighboring buildings. The window to wall ratio was considered. The definition of archetypes includes information on the average number of floors and building height, window-to-wall ratio, annual electricity consumption for heating and cooling, and U-values of exterior walls. The substitution of windows is not considered in this study. Monteiro [27] considered the existence of shops on the ground floor in residential buildings by removing outliers from the electricity consumption. Different systems of external thermal insulation are analyzed. Depending on the system and the final U-value after renovation, different material requirements are obtained. Combining the external façade areas of buildings, divided by archetype,

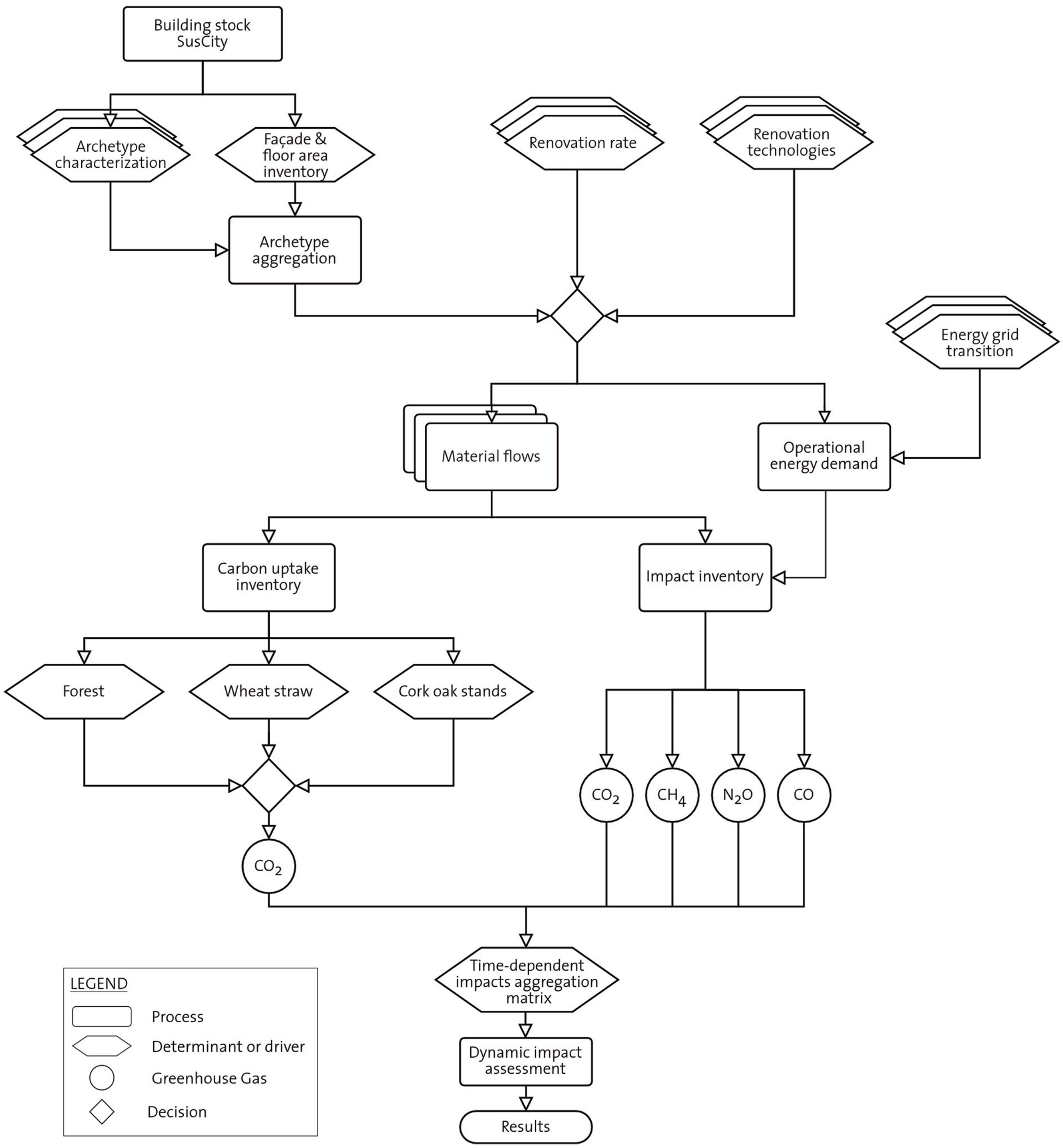


Fig. 1. Framework of the model.

with the different material requirements of retrofit systems and different yearly renovation rates, the material flows per type of material are provided, which subsequently allows analyzing the impacts of renovation over time.

Simultaneously, direct impacts from operational energy use for heating and cooling are calculated per year, considering the pre- and post-renovation thermal performance of buildings. The floor area which needs to be heated/cooled is obtained through GIS. Due to the scale of the case study and the renovation over time, there are two possibilities on how to account for impacts from the operational energy use (LC stage B6): firstly, only for the renovated buildings and secondly, for all buildings (renovated and non-renovated). The first seems more intuitive while the second makes more sense when analyzing the performance of the whole area, especially when looking at the carbon budget. Both possibilities will be discussed. Since this paper analyzes the renovation of external façade area but operational energy use is based on heated/cooled floor area, a coefficient referring to the relation between floor area and external façade area per archetype is used to convert façade into floor area and to calculate B6 impacts. These values can be found in Supplementary Information (SI) I.

Secondly, the material flows and energy needs are translated into an emission inventory, as well as into a carbon uptake inventory for the bio-based materials. For the emission inventory, the material quantities and operational energy needs are linked with emission coefficients for the greenhouse gases (GHG) CO_2, CH_4, N_2O, and CO. Fossil emissions, biogenic emissions, and land transformation emissions are considered. Different potential transitions of the energy grid are used to model the temporal dynamics of impacts related to operational energy demand. For the carbon uptake inventory, the type and amount of biomass used in the different renovation technologies is translated into the corresponding regenerated biomass in nature to guarantee a consistent supply. Species-specific rotation periods and carbon coefficients are considered. The sequestered carbon is expressed in CO_2 (1 kg of C equals 3.67 kg of CO_2).

Thirdly, the results from the impact and carbon uptake inventory are used to calculate the dynamic inventory result that considers the timing of GHG emissions and biogenic carbon uptake. For this purpose, the *DynCO$_2$* calculation tool [19] is used.

3.2. Case study

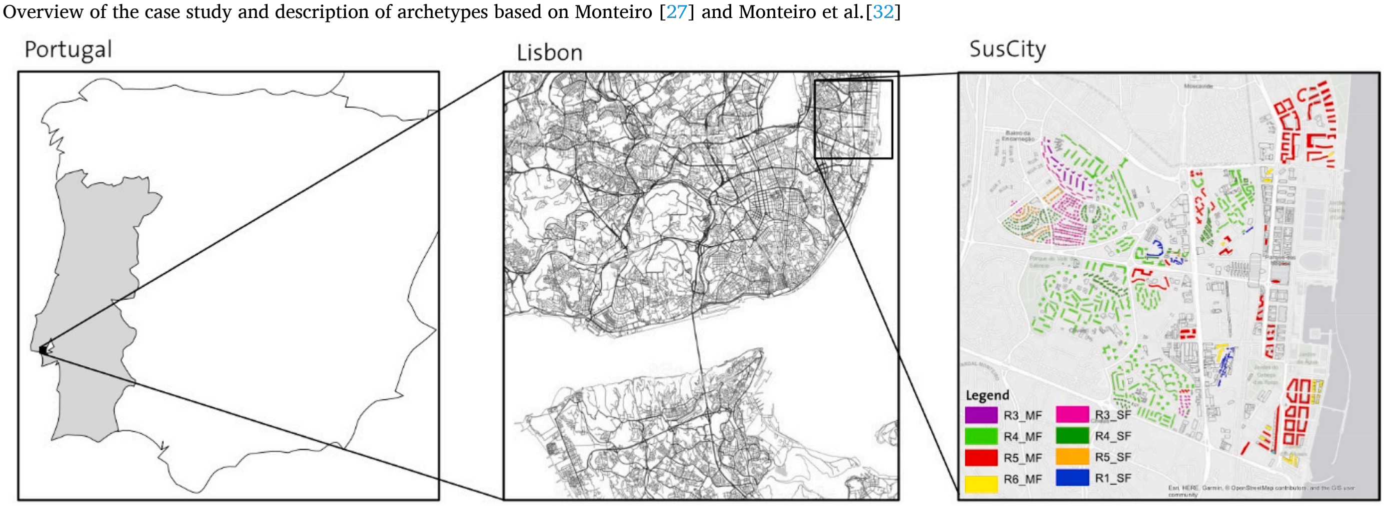
3.2.1. Dwelling stock under study

The *SusCity* area in Lisbon is chosen as a case study area. *SusCity* has been the testbed of various other research projects that want to promote sustainable urban transitions [28–32]. Therefore, an increased detail of data is available for this specific area. Moreover, since it refers to an agglomeration of neighborhoods (Olivais Velho, Encarnação, Olivais North and South, and Parque das Nações) that were constructed during different time periods, it represents different characteristics of an urban building stock at a relatively small scale. *SusCity* is located in the northeast of Portugal's capital Lisbon. Only dwellings (i.e. residential buildings) are included in the analysis. The characterization of the *SusCity's* dwelling stock into archetypes is taken from Monteiro et al. [27,32]. These authors obtained the current annual electricity consumption per archetype through a parametric energy model. A Lisbon survey revealed that 69% of households use electric systems for space heating (10% air conditioning units and 59% radiators), 22% natural gas systems (boiler), and 9% have no heating systems [27]. Table 1 shows the location of the *SusCity* area and details the eight different archetypes used. Their division is based on construction period and size class (single or multi-family). Buildings that were built between 1920 and 1945 account for less than 1% in the *SusCity* area and were therefore neglected. For this study, the archetypes are ranked by their current U-value, from the worst (highest) to the best (lowest) U-value. Buildings that are ranked worst are to be renovated first. In this way, a need-based renovation-strategy of buildings is analyzed.

3.2.2. Life cycle stages

This paper focuses on the thermal retrofit of existing buildings and considers the relevant Life Cycle (LC) stages: Replacement (B4), Refurbishment (B5) and Operational energy (B6), according to EN 15804:2012 [23]. A time span of 100 years is chosen, therefore including 2050 and 2100, which are milestones for climate mitigation. A sensitivity analysis of the time horizon, comparing results during 100 years with 200 years, can be found in SI II. During 100 years various renovation cycles occur. More specifically, the following LC stages are encountered during 100 years: the production and installation of the system, the replacement of the coating, the EoL of the original system and the production and installation of its substitution. Therefore, an adapted subdivision of LC stages, as presented in Table 2, was employed. The numbering of subdivisions does not mirror the occurrence of the described events in time, for example, here, *B4 Replacement of coating* occurs only after *B5 Production and installation of renovation system*. However, the definition of LC modules (B4, B5, B6) was kept to be able to categorize the impacts in accordance with EN 15804:2012 [23]. Later, Table 4 details the adapted subdivision of LC stages over time. The European standard does not instruct in which LC stage to account for benefits from carbon uptake of regrowing plants. We decided to account for it in module *B5 Refurbishment*, under an assigned subdivision, since it is the use of bio-based material in the construction technology for retrofit that causes the required regrowth of biomass. The FU of this study is 1 m^2 of retrofitted wall during 100 years with the target U-value of 0.15 W/m^2K. This target is used to define the amount of additional thermal insulation per archetype and is associated to the yearly energy consumption of 12 kWh/m^2*year for heating, and 12 kWh/m^2*year for cooling. The correlation between U-value and energy use for heating and cooling after retrofit is also based on Monteiro [27]. It is assumed that a comfortable indoor temperature can be guaranteed with 24

Table 1
Overview of the case study and description of archetypes based on Monteiro [27] and Monteiro et al.[32]



Archetype ID	R1_SF	R2	R3_SF	R3_MF	R4_SF	R4_MF	R5_SF	R5_MF	R6_MF
Construction period	before 1919	1920–1945	1946–1960	1946–1960	1961–1990	1961–1990	1991–2005	1991–2005	2006–2011
Size class	single family	–	single family	multi family	single family	multi family	single family	multi family	multi family
Share archetype	1%	0%	3%	1%	3%	38%	1%	47%	6%
U-value exterior walls [W/(m^{2}K)]	2.38	–	2.38	1.01	1.89	0.96	1.02	0.63	0.56
Annual electricity consumption [kWh/m^2]	57.2	–	46.9	36.4	44.5	36.2	43.8	34.3	34.5
Number of floors	1	–	2	4	2	6	2	8	7
Window to wall ratio	10%	–	8%	19%	8%	27%	8%	31%	29%

Table 2
Adapted description of LC stages as used in the present study.

LC stage	Name (EN 15804)	Adapted Subdivision	Subdivision description
B4	Replacement	*B4 Replacement of coating*	Production, installation and EoL of mortar and finishing (every 30 years)
B5	Refurbishment	*B5 Production and installation of the retrofit system*	Production and installation of the retrofit system including all parts and materials (for initial retrofit)
		B5 Carbon uptake in nature	Carbon sequestration of plants (for initial and repeated retrofit)
		B5 EoL of the whole retrofit system	Decommissioning, transport to waste processing, waste processing, disposal (for initial and repeated retrofit)
		B5 Replacement of the whole retrofit system	Production and installation of the retrofit system including all parts and materials (for repeated retrofit every 60 years)
B6	Operational energy use	*B6 Operational energy use*	Operational energy use for heating and cooling

kWh/m^2*year. The Portuguese Passivhaus Association [33,34] suggests a maximum 15 kWh/m^2*year each for heating and cooling.

Potential summer overheating due to a high level of insulation is not studied here. Only additional external thermal insulation for the vertical area of the building envelope is considered. The common other components of deep renovation (replacement of the heat generator and the installation of complementary system components such as distribution pipes, installation of PV panels, and the replacement of windows) are not considered for the calculation of impacts but can be generally recommended to guarantee comfortable indoor temperatures at low energy consumption levels. Moreover, the present study is limited by the assumption that during the next 100 years buildings will be renovated instead of demolished and substituted through new buildings. It should be noted that licensed (partial and total) demolition works corresponded to 7.2% in 2019, and 7.7% in 2018, of total licensed construction works in Portugal [35]. In Lisbon, circa 300 buildings were demolished between 2007 and 2017 [36].

3.2.3. Thermal insulation system for external walls

A conventional scenario and two bio-based systems for external thermal retrofit are analyzed:

- A combination of external thermal insulation composite systems (ETICS) made with expanded polystyrene (EPS) and with stonewool represent the conventional scenario. It is assumed that ETICS with EPS accounts for 91% and ETICS with stonewool for 9% based on the market share of insulation materials in Southern Europe [37];
- "TES" is a prefabricated timber-based element system, developed by an ERA-NET funded research consortium to improve the energy efficiency of the building envelope [38]. It can be combined with different types of thermal insulation material. The present study analyzes injected wheat straw as thermal insulation. TES is directly mounted to the existing exterior wall. It does not require any preconditioning of the wall thanks to straw that is blown into the gap between the wall and the TES system to level out any irregularities. For this study, the system was adapted for the Portuguese context, using injected straw as insulation;
- ETICS with insulation cork board (ICB). ICB is a natural thermal insulation also known as expanded cork agglomerate [39]. Cork is generally harvested every 9 years from the cork oak's bark [40]. In Europe, cork oak savannahs are mainly predominant in Portugal, Spain, Italy and France, covering about 1.5 Mio ha land [41]. The raw material cork faces high inter-sectoral competition because it is predominantly used to produce bottle cork stoppers. Therefore, a large-scale application of ICB in construction is unlikely. However, ICB serves well as a local material solution for the renovation of SusCity.

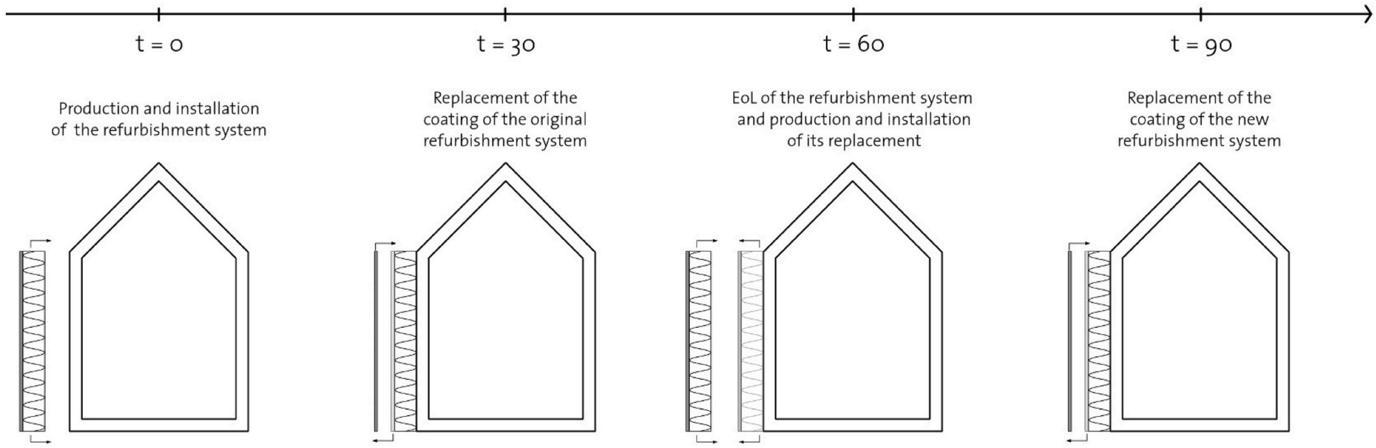
The construction technologies for retrofit under study are described in Table 3. Incineration is defined as the waste treatment for all bio-based components of the system, which can be considered a worst case scenario because it releases the stored biogenic carbon as CO_2 back to the atmosphere at the EoL. If despite the incineration of biomass, the

Table 3
Materials inventory for the studied retrofit systems.

Name	Layers		Thickness	Density	Thermal conductivity	Weight	Life span	Waste treatment
			mm	kg/m^3	W/(m*K)	kg/m^2	years	
TES	1	Mineral coating	20	565	0.820	11.30	30	Inert landfill
	2	Straw	var	105	0.043	var	60	Incineration
	3	Stud/Beam (timber)	n.a.	700	0.120	17.38	60	Incineration
	4	OSB	4	650	0.130	2.60	60	Incineration
	5	Straw	45	105	0.043	4.73	60	Incineration
ETICS with ICB	1	Mineral coating	20	565	0.820	11.30	30	Inert landfill
	2	Metallic screws	n.a.	n.a.	n.a.	0.01	60	Recycling
	3	Plastic dowels/fixings	n.a.	n.a.	n.a.	0.08	60	Recycling
	4	Glass fiber mesh	20	n.a.	n.a.	0.14	60	Inert landfill
	5	Metallic profile	n.a.	n.a.	n.a.	0.19	60	Recycling
	6	ICB	var	110	0.040	var	60	Incineration
ETICS with EPS	1	Mineral coating	20	565	0.820	11.30	30	Inert landfill
	2	Metallic screws	n.a.	n.a.	n.a.	0.01	60	Recycling
	3	Plastic dowels/fixings	n.a.	n.a.	n.a.	0.08	60	Recycling
	4	Glass fiber mesh	20	n.a.	n.a.	0.14	60	Inert landfill
	5	Metallic profile	n.a.	n.a.	n.a.	0.19	60	Recycling
	6	EPS	var	30	0.036	var	60	Incineration
ETICS with stonewool	1	Mineral coating	20	565	0.820	11.30	30	Inert landfill
	2	Metallic screws	n.a.	n.a.	n.a.	0.01	60	Recycling
	3	Plastic dowels/fixings	n.a.	n.a.	n.a.	0.08	60	Recycling
	4	Glass fiber mesh	20	n.a.	n.a.	0.14	60	Inert landfill
	5	Metallic profile	n.a.	n.a.	n.a.	0.19	60	Recycling
	6	Stonewool	var	30	0.037	var	60	Inert landfill

Note to Table 3: Conventional ETICS is described in section 3.2.3. "var" refers to a variable thickness of insulation depending on the archetype as described in 3.2.2. "n.a." refers to different measurements that cannot be expressed in thickness per m^2.

Table 4
Overview of emission and uptake inventory for 1 m^2 of refurbished façade and visualization of the considered life cycle stages during the first 100 years. Data taken from Refs. [8,39,54–58].



	t = 0	t = 30	t = 60	t = 90
TES				
biogenic carbon storage [kg CO_2]	−114.90	0.00	−114.90	0.00
kg CO_2	13.44	3.65	80.22	3.65
kg CH_4	2.50E-02	1.51E-02	2.60E-02	1.51E-02
kg N_2O	3.60E-03	9.19E-05	3.62E-03	9.19E-05
kg CO	3.92E-02	9.43E-03	4.18E-02	9.43E-03
ETICS with ICB				
biogenic carbon storage [kg CO_2]	−69.10	0.00	0.00	−69.10
kg CO_2	9.32	3.66	44.00	3.66
kg CH_4	3.23E-02	1.51E-02	3.06E-02	1.51E-02
kg N_2O	4.29E-04	9.21E-05	4.34E-04	9.21E-05
kg CO	6.73E-02	9.46E-03	6.17E-02	9.46E-03
Conventional ETICS				
kg CO_2	6.92	3.66	6.83	3.66
kg CH_4	2.44E-02	1.51E-02	2.25E-02	1.51E-02
kg N_2O	2.75E-04	9.20E-05	2.85E-04	9.20E-05
kg CO	2.80E-02	9.45E-03	2.20E-02	9.45E-03

bio-based retrofit systems are advantageous compared to conventional systems then the advantage can only increase with an improved waste treatment. For a detailed analysis of waste treatment categories of bio-based construction please refer to Pittau et al. [8,22] who identified recycling as the most efficient waste treatment to reduce the EoL impacts for systems with a high amount of bio-based material. This is in line with cascading of biomass, which refers to the use of the same material unit in multiple, successive product cycles [42,43].

A common concern of bio-based construction is increased fire hazard. For the studied systems in this paper it should be noted that:

- The TES developers propose specific design guidelines to prevent fire from spreading in buildings, including the construction of fire stops around windows, between stories and vertical elements [38];
- ICB produced by the Portuguese manufacturers Amorim [44] and Sofalca [45] have a fire resistance of Euroclass E, which is in line with other common insulation products like EPS and PUR. This means that they should only be used safely behind a thermal screen (e.g. gypsum plasterboard, mineral coating) [46].

Wheat and consequently straw has short rotation periods of one year or less. In contrast, trees take decades to grow. It is assumed that the plants sequester carbon at a constant rate during their growth. In reality, carbon sequestration is a complex process that depends on the species and on the speed of growth [47], also it is, in fact, non-linear [48]. Modeling it linearly overestimates the carbon sequestration potential of biomass, with longer rotation periods resulting in higher overestimations.

The following rotation periods were considered as a reference:

· 1 year for wheat straw;
· 75 years for pine wood [49];
· 9 years for cork oak bark [50];

Table 4 visualizes the LC stages, which were listed in Table 2, and shows the moment in time when they are considered. Table 4 also shows the emission inventory for CO_2, CH_4, N_2O, and CO for 1 m^2 of renovated façade for the three studied retrofit systems. The data sources for Table 4 can be found in SI III. The production and installation of the renovation system occurs at time 0 (B5). This is also when the carbon of the bio-based components is moved into the building and stored there (B4). The following values were assumed for the carbon content of biomass:

· 0.40 $C/kg_{biomass}$ for wheat straw [51].
· 0.50 kg $C/kg_{biomass}$ for pine wood [52].
· 0.55 $C/kg_{biomass}$ for cork oak bark [53].

The replacement of the coating as a maintenance measure occurs after 30 years (B4). At time t = 60 the original retrofit system reaches its EoL (B5) and needs to be replaced with a new system (B5), that is assumed to have the exact same characteristics as the original one. After another 30 years, at time t = 90, the coating is replaced again.

3.2.4. Scenario analysis for renovation rates and energy grid transitions

Two scenarios for the renovation rates and three scenarios for the transition of the energy grid are analyzed. More specifically, a business as usual (BAU) annual renovation rate of 0.4%, based on past renovation rates [59], is defined. The BAU rate is compared to an increased rate of 3.3% that would allow for the whole SusCity dwelling stock to be renovated by 2050. This ambitious goal is in line with a proposed 3% renovation rate across Europe to achieve a climate neutral building stock by 2050 [11,60].

For the possible transition of the energy grid, the status quo is compared with two scenarios that reduce the emissions per consumed kWh of electricity to 1% in 2050 compared to today's values. The underlying assumption is that by 2050 a major transition to renewable energy sources, which should mostly be concentrated on solar power, off-shore and on-shore wind, and hydropower, will be completed in Portugal. This is in line with the Portuguese Carbon Neutrality Roadmap (RNC) for 2050 [61]. The scenario is based on the Transition Pathway Explorer, an online model developed during a Horizon2020 project [62]. Specifically, the "ambitious" pathway for Portugal is selected. It needs to be noted that policy-makers often propose an increased share of (only) two-thirds for renewable energy in 2050 [63]. The possible transition pathways until 2050 to reduce to 1% of present emission intensity is modeled as a convex curve (decreasing exponential function) and as a concave curve (decreasing quadratic function). The parameters of the two curves were adjusted (i.e. −0.0099 for the exponential function, and −0.000104705 for the quadratic function) to reflect the reduction to 1%.

4. Results

4.1. Impacts for the retrofit of 1 m^2

The exemplary CO_2 inventory for 1 m^2 of refurbished façade for archetype R1_SF over a 100 year period is shown in Fig. 2. The values are taken from the inventory in Table 4 that shows the collected data for all alternatives. The conventional ETICS scenario (91% EPS and 9% stonewool) refers to lightweight systems, therefore resulting in a comparably lower CO_2 inventory (17.4 kg of CO_2 for LC stages B4 and B5). The heavier systems made with cork or with timber and straw result in 57.0 kg of CO_2 (ETICS with ICB) and in 97.3 kg of CO_2 (TES) for LC stages B4 and B5 excluding B5 carbon storage. However, for the bio-based components −69.1 kg of CO_2 storage for ETICS with ICB, and −114.9 kg of CO_2 storage for TES, need to be added. Since TES does not only include biomass in the insulation layer (straw) but also wood for the frame, its carbon storage potential is higher than for ETICS with ICB, which only uses biomass in the insulation layer. This adds up to a total for LC stages B4 and B5 of −12.1 kg of CO_2 for ETICS with ICB and −17.6 kg of CO_2 for TES. As expected, LC stage B5 (EoL of the system) causes high impacts for TES and ETICS with ICB due to the incineration of biomass.

Fig. 3 compares the three different renovation systems for the three types of outputs obtained with *DynCO₂* [19]. On the left, GWI_{inst} is illustrated. For the bio-based systems, the instantaneous radiative forcing becomes negative after 1 year thanks to the regrowth of biomass in nature. Initially, the curve for TES drops faster than the one for ETICS with ICB since straw is a fast-rotation crop that recovers the stored carbon in nature within one year, while the bark of the cork oak takes 9 years to regrow. However, after the 9 years are reached the impacts start to rise for ETICS with ICB, while for TES they keep on growing in negative values thanks to the longer rotation period of wood in nature, which is used for the TES frame. After 30 years, in 2050, the coating layer is replaced leading to a small increase in impacts. After 60 years, in 2080, the system reaches its EoL, adding the impacts related to the EoL and the production and installation of a new system into the building. Since TES includes more biomass than ETICS with ICB, the assumed EoL scenario with incineration of biomass leads to a total higher impact for TES than for ETICS with ICB. However, after another 5 years, in 2085, the radiative forcing of ETICS with ICB already falls below the conventional ETICS. TES takes until 2088 to fall below the conventional ETICS. This is again related to the different rotation periods of the biomass. In the middle, Fig. 3 shows GWI_{cum}. The cumulative radiative forcing for the conventional ETICS can only increase over time, with a sharp increase of impact related to B5 End of Life and B5 Replacement of the retrofit system. TES has the highest negative GWI_{cum} at all times. This also translates to GWP_{dyn}, as shown on the right of Fig. 3. In the critical year 2050, the GWP_{dyn} of 1 m^2 renovated façade, in kg of CO_2 eq., is −21.1 for TES, −18.8 for ETICS with ICB and 8.8 for conventional ETICS.

4.2. Impacts for the external retrofit of the SusCity area

In this section, the impacts at the urban scale are presented. Fig. 4 compares the GWI_{inst}, GWI_{cum} and GWP_{dyn} for the three different renovation system considering two renovation rates for LC stages B4 and B5. It becomes clear that bio-based renovation offers the opportunity to become climate positive (negative GWI_{cum}), while the reference case (BAU rate and conventional ETICS) leads to $3.5 * 10^{-8}$ kW/m^2 in 2050 and $21.7 * 10^{-8}$ kW/m^2 in 2100. Moreover, the differences between the BAU rate and the increased rate of 3.3%, is significant. For example for GWI_{cum} for TES: in 2050 the increased renovation rate results in −45.4 *

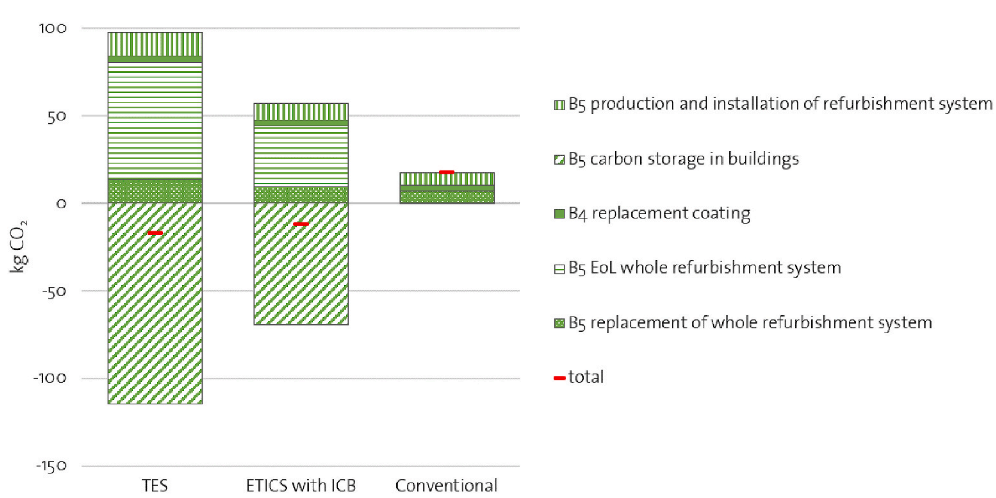


Fig. 2. CO_2 emission and uptake inventory for 1 m^2 of refurbished R1_SF façade during the first 100 years.

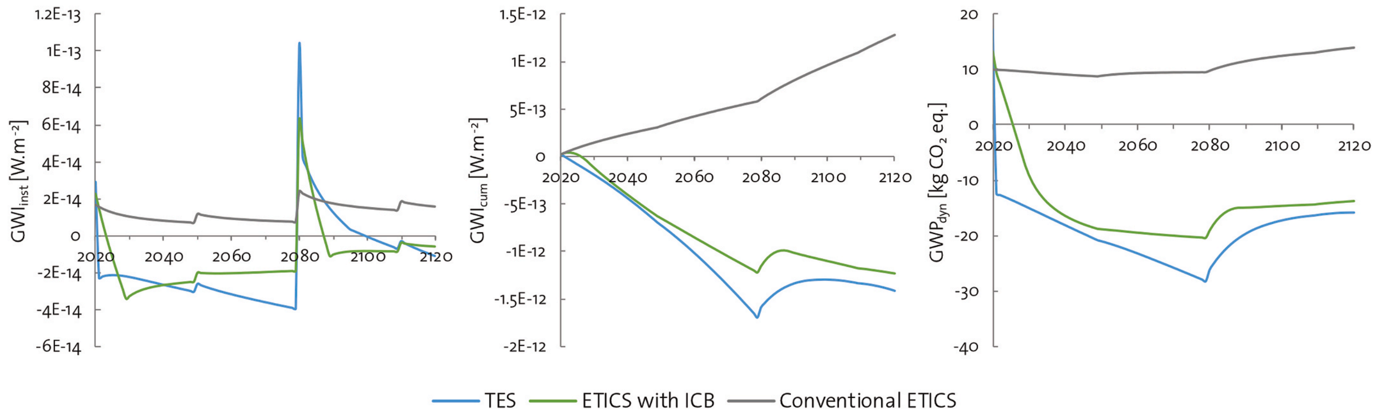


Fig. 3. Instantaneous impact (left), cumulative impact (middle), and dynamic GWP (right) of 1 m^2 of R1_SF façade that is installed in the building in 2020 for the LC stages B4 and B5.

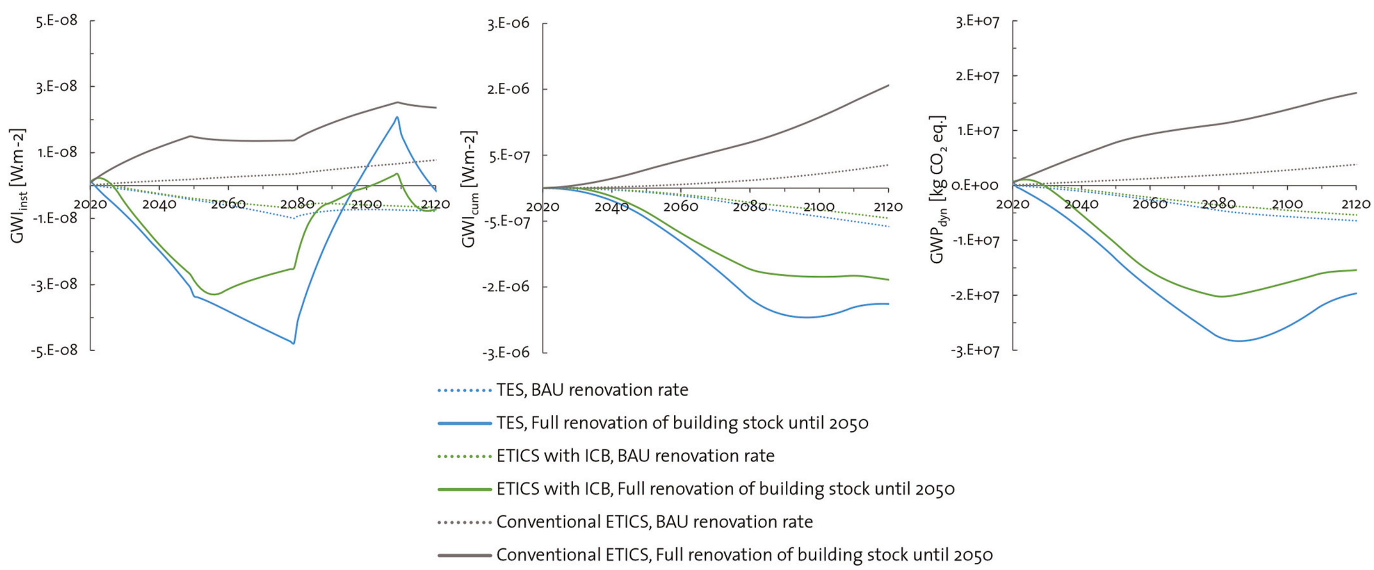


Fig. 4. Instantaneous impact (left), Cumulative impact (middle), and dynamic GWP (right) of the renovation (LC stages B4 and B5) of the SusCity area.

10^{-8} kW/m^2 and the BAU rate in $-6.1 * 10^{-8}$ kW/m^2, meaning a 7.5 higher (negative) value. In 2100 it is still 4.5 times bigger. Because of the species rotation periods, ETICS with ICB only becomes climate positive (GWI$_{cum}$ negative) after 2029, while TES only takes one year to become negative. Both, urban-scale renovation with TES and with ETICS with ICB, result in negative impacts in 2050 and 2100, while conventional ETICS are always positive and increasing. ETICS with ICB has a lower GWI$_{inst}$ starting from 2096. Yet, in cumulative terms (GWI$_{cum}$), TES is the lowest in 2050 and in 2100. The results for GWP$_{dyn}$ are similar and can be seen on the right of Fig. 4. All values are presented in SI IV.

The bottom-up building stock model allows dissecting the results by archetype. The contribution of each archetype to the GWP at 100 years calculated with DLCA (GWP$_{dyn,100}$) for the whole SusCity dwelling stock is shown in Fig. 5. The BAU rate of 0.4% does not allow all buildings to be renovated until 2050. Due to the prioritization of archetypes by retrofit need, the older buildings with highest U-values, i.e. the single-family archetypes R1_SF, R3_SF and R4_SF are renovated first. Out of these three, R3_SF has the highest archetype share. Therefore, for the BAU renovation rate the archetype that contributes the most to the GWP$_{dyn,100}$ in 2050 and in 2100 is R3_SF. The increased renovation activity of 3.3%, which enables all dwellings in the SusCity area to be renovated until 2050, leads to absolute higher values of GWP$_{dyn,100}$. For this higher annual renovation rate, the archetype that contributes the most to the GWP$_{dyn,100}$ of LC stages B4 and B5 in 2050 and in 2100, is the multi-family R4_MF. The total impact of the older single-family archetypes (R1_SF, R3_SF, R4_SF) is the same for both renovation rates. However, the relative impact of these archetypes decreases with the increased renovation rate of 3.3%, which allows for more buildings to be renovated. Since the multi-family buildings (especially R4_MF and R5_MF) represent a bigger archetype share, their renovation also leads to an absolute higher impact.

As was shown in Fig. 4, TES is the most promising renovation system, meaning it has the highest negative impacts in terms of GWI$_{cum}$ and GWP$_{dyn}$ for the LC stages B4 and B5. However, to get the complete picture and to answer the question if renovation can lead to a climate neutral dwelling stock, we need to consider also the impacts from LC stage B6. Table 5 shows the impacts for TES for the LC stages B4 and B5, as well as for B6. Buildings after renovation are assumed to require 15 kWh/m2 for annual space heating and cooling. Table 5 lists the impacts for the two possibilities on how to account for B6 impacts: only for the renovated buildings or for all buildings (renovated and non-renovated). The B6 impacts for the BAU renovation rate are lower than for the 3.3% rate, when only accounting for renovated buildings, since less buildings are renovated and therefore considered with the BAU rate. When considering all buildings then the 3.3% rate translates to a total reduced amount of heating and cooling. Depending on the accounting method for B6, the embodied impacts (B4 and B5) can only relate to 0.2% of the total operational and embodied impacts (B4+B5+B6), meaning the

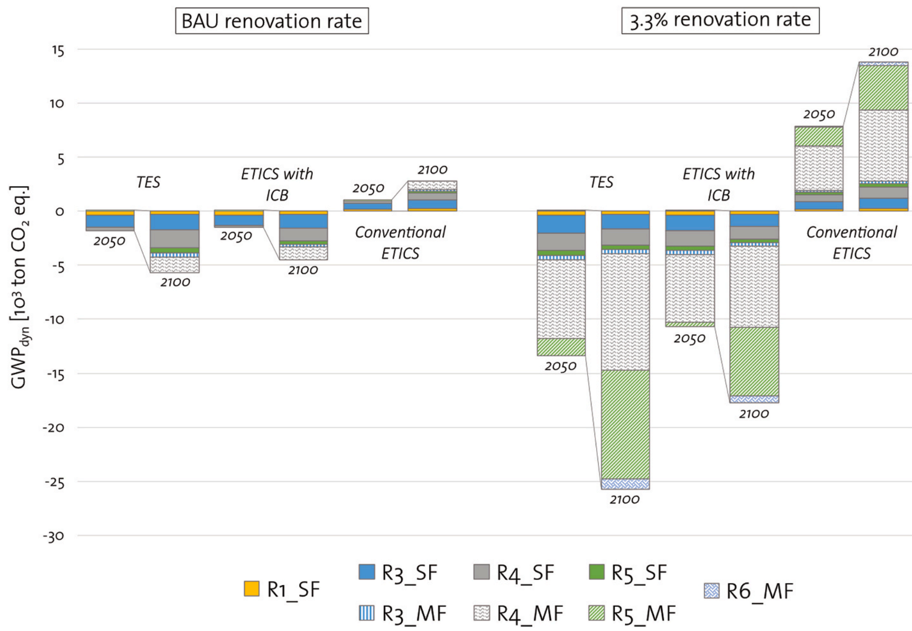


Fig. 5. Contribution of archetypes to $GWP_{dyn,100}$ for the LC stages B4 and B5. Comparison of the different retrofit systems and renovation rates under study for the years 2050 and 2100.

Table 5
GWI_{cum} for the SusCity renovation with TES, comparing impacts related to LC stages B4 and B5, with B6 only for renovated and for all buildings.

		2050	2100
BAU renovationrate	B4+B5 [W.m^{-2}]	−6.1E-08	−4.3E-07
	B6 only for renovated buildings [W.m^{-2}]	2.7E-07	4.5E-06
	Total GWI_{cum} [W.m^{-2}]	**2.1E-07**	**4.1E-06**
	(B4+B5)/Total GWI_{cum}	**18.6%**	**8.8%**
	B4+B5 [W.m^{-2}]	−6.1E-08	−4.3E-07
	B6 for all buildings [W.m^{-2}]	2.5E-05	1.2E-04
	Total GWI_{cum} [W.m^{-2}]	**2.5E-05**	**1.2E-04**
	(B4+B5)/Total GWI_{cum}	**0.2%**	**0.3%**
Increased renovation rate	B4+B5 [W.m^{-2}]	−4.5E-07	−2.0E-06
	B6 only for renovated buildings [W.m^{-2}]	3.9E-06	4.4E-05
	Total GWI_{cum} [W.m^{-2}]	**3.4E-06**	**4.2E-05**
	(B4+B5)/Total GWI_{cum}	**10.5%**	**4.2%**
	B4+B5 [W.m^{-2}]	−4.5E-07	−2.0E-06
	B6 for all buildings [W.m^{-2}]	1.9E-05	8.2E-05
	Total GWI_{cum} [W.m^{-2}]	**1.9E-05**	**8.0E-05**
	(B4+B5)/Total GWI_{cum}	**2.3%**	**2.3%**

choice of material seems negligible. However, when only looking at the impacts of renovated buildings then the embodied impacts (B4+B5) can account for up to 18.6%. GWI_{cum} for the LC stages B4 and B5 for TES is always negative. However, the total impacts (B4+B5+B6) are always positive, no matter the renovation rate and consideration of renovated and non-renovated buildings, meaning it seems impossible to turn the SusCity dwelling stock climate neutral.

5. Discussion

5.1. Putting the results into context

The only study that we found to be directly comparable to this one is by Pittau et al. [8], which analyzed retrofit of the EU dwelling stock with different bio-based materials. As in this paper, Pittau et al. [8] employed a dynamic LCA based on Levasseur et al. [16]. Specifically, their "STR" system, which is an I-joist frame with pressed straw (with their EoL scenario DS2 and without accounting for module D), is comparable to TES as studied here. We extracted data for Portugal that is provided in the supplementary data of Pittau et al. [8], and further scaled it down, using the number of inhabitants, to the size of SusCity. The chosen time frame for comparison is 100 years from the start of analysis. In this study, $-5.8 * 10^{-7}$ W/m^2 for GWI_{cum} and $-6.4 *10^3$ tons CO_2 eq. for GWP_{dyn} were obtained for 2120 with a BAU renovation rate. The scaled down values from Pittau et al. [8], are -2.7 * W/m^2 for GWI_{cum} and $-3.02*10^3$ tons CO_2 eq. for GWP_{dyn} for the same time horizon. The difference, between this study and Pittau et al.'*s* [8], can be justified as follows: here, the BAU renovation rate refers to 0.4%, while Pittau et al. [8] assumed 0.1%. Moreover, in TES the straw is in-blown while in the "STR" system pressed straw was used, which results in slightly different impacts of manufacturing the renovation systems.

In addition, the following studies are worth mentioning to get a better understanding of methodological differences:

Zieger et al. [64] presented a dynamic LCA from cradle-to-grave of a bio-based wall made with timber and straw. In contrast to this study, their analyzed wall was load-bearing and the authors chose a FU of 1 m^2 with a U-value of 0.137 W/m^{2}K. Their straw layer had a thickness of 370 mm. Their results range from −9.8 to −22.2 kg of CO_2 eq. per 1 m^2. To put this in relation with the present study: as presented in Fig. 2, for the retrofit of 1 m^2 of the archetype R1_SF with TES (referring to 145 mm of insulation straw layer), the total CO_2 emission and uptake inventory is −17.59 kg of CO_2 eq. This is in range with the values obtained by Zieger et al. [64]. However, as stated, the two studies vary both in methodological aspects, as well as in choice of studied wall system.

Negishi et al. [65] studied a timber frame with a dynamic LCA for the FU of three single attached buildings with a total floor area of 414 m^2 houses during 50 years. Besides the different system and FU, their study differed from this one since the authors accounted for carbon uptake before construction, meaning they considered that the trees grow before the use of the harvested wood product. In contrast, this study considers that trees (and other sources of biomass) grow after harvesting. Hoxha et al. [66] explains these different dynamic approaches in more detail. A comparison between results, therefore, seems pointless.

García-Pérez et al. [25] studied external thermal retrofit with ETICS with ICB of different building types in Barcelona by conducting a static LCA from cradle-to-gate of 1 m^2. For buildings that were built before 1981 they obtained +15 kg of CO_2 eq. per m^2, accounting for the carbon capture in a static way according to a −1/+1 approach [66]. In this study, we obtained −12.12 kg of CO_2 eq. for the renovation of 1 m^2 of archetype R1_SF with ETICS with ICB. The difference in results between the two studies can be explained by García-Pérez et al.'s [25] disregard of the timing of carbon uptake and GHG emissions.

5.2. Understanding the dynamics of urban scale renovation to define strategic actions

The following subsections discuss the important dynamic parameters of the present analysis i) material choice; ii) annual renovation rate; iii) dwelling stock characteristics and the need-based prioritization of renovation, and iv) energy supply for space heating and cooling.

5.2.1. Choosing renovation systems with a high amount of (fast-growing) biomass

Three different external thermal insulation composite systems for building walls were analyzed. Two of them use bio-based components, namely TES, and ETICS with ICB. The third one was a combined scenario of two ETICS systems made with EPS and stonewool to represent the conventional solution for thermal retrofit in Portugal. Accounting for the impacts and carbon uptake during LC stages B4 and B5, it was shown at two scales, namely for the declared unit of 1 m^2 of retrofitted external wall, and for the SusCity dwelling stock, that using bio-based materials allows going climate-positive by reaching negative radiative forcing (GWI_{cum}). The TES system allowed for the highest negative values thanks to the use of biomass, not only in the insulation layer, namely straw, but also timber in the frame. Moreover, TES allowed for almost immediate negative radiative forcing since straw is a fast-rotation crop. Therefore, bio-based renovation systems are advantageous compared to conventional systems regarding embodied impacts thanks to the carbon uptake of regenerated biomass. Moreover, using wood for the structural part of the system provides additional opportunities of carbon uptake in nature, and the shorter the rotation period of the biomass the faster the carbon uptake. Yet, the total impacts of LC stages B4, B5 and B6 showed that a climate neutral dwelling stock cannot be achieved by only renovating external façades, not even with an increased renovation rate that allows renovating all dwellings until 2050 and not even when using the bio-based system TES. Also, it should be noted that there are concerns regarding the land availability and feasibility of large-scale construction and renovation with timber, as discussed in Pomponi et al. [67].

Furthermore, it should be noted that the fixed time horizon of 100 years leads to temporal cut-offs and to the question of inter-generational equality due to the carbon emissions of the biomass at the EoL [18,68]. For this purpose, we extended the time horizon of the analysis to 200 years. The results of this sensitivity analysis can be found in SI II. They show that using bio-based materials now, during the energy grid transition, provides benefits over a long time.

5.2.2. Increasing the annual renovation rate

It seems crucial to stimulate the current low renovation rate of 0.4% annually because only if a building is actually renovated, it allows to store carbon in the renovation system and to reduce the operational energy use for heating and cooling thanks to the improved thermal performance. It was shown that for TES, the increased renovation rate of 3.3%, which allows for all SusCity dwellings to be renovated until 2050, results in a 7.5 times higher negative GWI_{cum} in 2050 than with the BAU renovation rate.

The European think-tank BPIE recently released an analysis highlighting the opportunity of renovating the European building stock to mitigate climate change and to recover from the economic damage of the COVID-19 pandemic [69]. They suggest scaling up serial renovation of buildings, relying on prefabricated building modules, which allow accelerated cost-effective renovation and bypassing the problem of lacking a trained workforce [69]. This argument also favors TES, since it is a prefabricated system. In Germany for example, the national agency for energy is currently supporting a three-year pilot project, joining forces with industry partners, to promote serial renovation [70].

5.2.3. Considering building stock characteristics for prioritized building renovation

For the analysis, buildings with higher improvement potential of U-value were prioritized. In fact, a prioritized renovation of poorly insulated buildings is currently under discussion for the Portuguese long-term strategy for building renovation [71]. An additional sensitivity analysis provides insight into the importance of a "prioritized strategy", compared to normal renovation activities where, on average, equal shares of building types are renovated every year ("no strategy"). Fig. 6 compares these two scenarios for renovation with TES, assuming a BAU annual renovation rate of 0.4%, which means that 12% of the total SusCity dwelling stock can be renovated until 2050. On the left of Fig. 6, it is shown that without a strategy, 12% of each archetype will be renovated until 2050, while, with the prioritized strategy, the renovation of the archetypes with the highest ranked U-values (R1_SF, R3_SF, R4_SF) can be completed until 2050, the renovation of R5_SF started, and the renovation of the remaining archetypes is postponed to after 2050. The benefits from the prioritized strategy are twofold. Firstly, it allows for more carbon uptake until 2050 thanks to the preferred installation of renovation systems with a thicker insulation layer of biomass. This means that the total impacts and carbon uptake for LC stages B4 and B5 until 2050, as shown in the middle of Fig. 6, are $-1.46 * 10^3$ tons CO_2 eq. without a strategy vs. $-1.79 * 10^3$ tons CO_2 eq. with the prioritized strategy. Secondly, it reduces the amount of total energy needed for heating and cooling and, therefore, LC stage B6 impacts, because the higher improvement potential of poorly-insulated buildings is tapped earlier in time. The right part of Fig. 6 compares the impacts related to LC stage B6: 100% refers to the impacts that are encountered without a strategy. For the archetypes R1_SF and R3_SF, impacts related to LC stage B6 are smaller (i.e. $< 100\%$) with a prioritized strategy because most of those buildings are renovated earlier in time. For R4_SF there is almost no difference between no strategy and a prioritized strategy. This is because, even though without a strategy only 12% of this archetype can be renovated until 2050, the earlier renovation of these buildings leads to earlier savings of energy expenses and therefore, levels out the complete renovation of all R4_SF buildings in the prioritized strategy, which only starts in 2035 (refer to SI V). For the remaining archetypes R5_SF, R3_MF, R4_MF, R5_MF, R6_MF, "no strategy" leads to a slightly reduced GWP_{dyn} of LC stage B6 because at least 12% of these archetypes can be renovated and their renovation starts already in 2020, while with a prioritized strategy their renovation gets delayed. In total, GWP_{dyn} of LC stage B6 is 3% smaller with a prioritized strategy than without. Therefore, considering that the impacts from LC stage B6 outweigh the impacts from LC stages B4 and B5, as was shown in Table 5, the prioritization of buildings renovation only offers a small savings potential of total LC stages impacts B4, B5 and B6 (4%) for the case study SusCity. That is because, in SusCity, the poorly thermal insulated single-family buildings account only for a small share of the stock and the difference in terms of U-values of the remaining multi-family buildings is small. However, in other places, with a higher variety of buildings' thermal characteristics and a bigger share of poorly performing buildings, incentivizing building owners of buildings with low thermal performance could result in significant decreased total impacts of building stock renovation (for the total of LC stages B4, B5 and B6).

A prioritization strategy would require programmed incentives so that owners of buildings with a low thermal performance are encouraged to renovate sooner than later. Various instruments to incentivize exist [72], for example: financial support (grants, tax relief, or loans) to provide a cost-effective intervention [58]; risk reduction (public loan

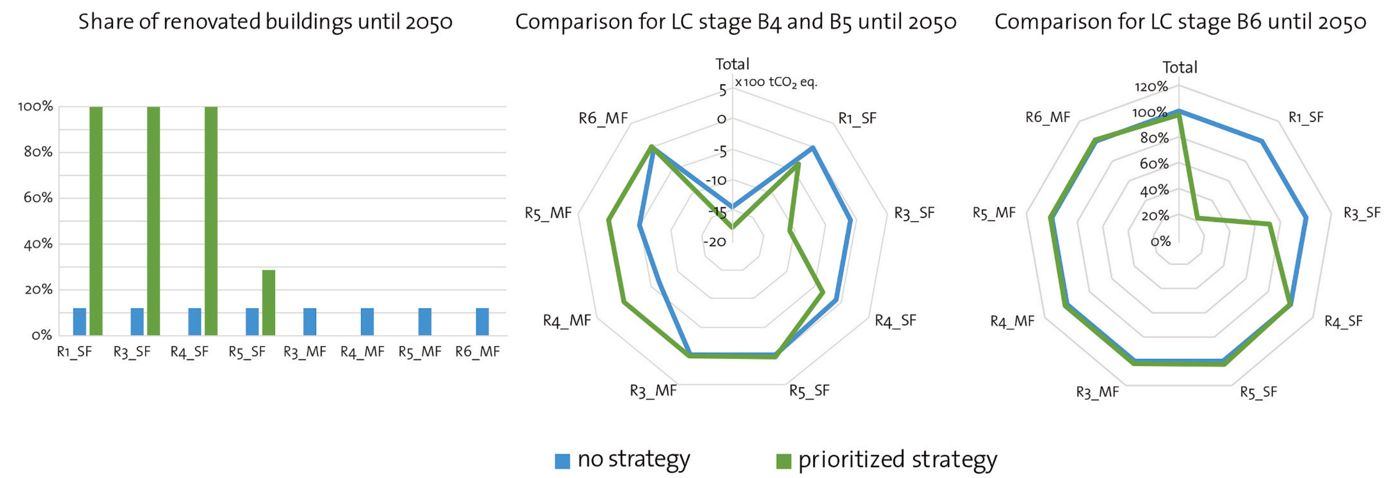


Fig. 6. Sensitivity analysis of renovation strategies until 2050.

guarantees, enabling project aggregation, or renovation of real estate portfolios); and the removal of legal barriers (acceleration of permit procedure). This range could allow targeting different types of building owners. Since the definition of archetypes used in this study refer to the type of dwelling (single-family or multi-family), as well as to size class, an additional socio-economic analysis could identify types of owners.

5.2.4. *The importance of a fast energy grid transition*

The global carbon budget, to keep global warming by 2050 below 2 °C, was approximately 800 Gtons in 2015 [73,74]. This value is rapidly shrinking and in 2020 only about 660 Gtons remain [75]. According to the International Energy Agency, the construction industry accounts for 11% of global energy-related emissions and indirect emissions from residential energy use for heating and cooling for another 11% [76]. The global carbon budget can be scaled down using different indicators (usually population or GDP) [62]. Portugal's population is 10.3 Mio [77] and the number of residents in the SusCity area is 33′659 [27]. Renovation accounted for 25.3% of licensed construction works in Portugal in 2018 [59]. Considering these values, the downscaled carbon budget of the SusCity area until 2050 for renovation, as well as for heating and cooling of all buildings, amounts to roughly 397 * 10^3 tons of CO_2. Fig. 7 plots the carbon budget in comparison to the impacts related to LC stages B4, B5 and B6, which arise from the renovation of SusCity dwellings with TES (the most promising bio-based system studied here) and a prioritized strategy in which poorly thermal insulated buildings are renovated first. Additionally, the figure includes three different scenarios for the transition of the energy grid until 2050: the first scenario refers to no transition of the current energy grid, which was used until now to calculate impacts related to LC stage B6. The second and third scenario refer to two possible transition pathways to reduce to 1% of present emission intensity, modeled as a convex curve and as a concave curve, respectively. ETICS with ICB and conventional ETICS, produce very similar results to the ones shown in Fig. 7 for TES, since they all have the same U-value after renovation and since the impacts from LC stage B6 dominate the total impacts during the total studied time horizon. The results for all studied renovation systems, total and divided by LC stage, can be found in SI IV. The figure shows that, in direct comparison (for the same energy grid scenario), an increased renovation rate, compared to the BAU rate, allows to reduce impacts but not enough to stay within the 2 °C budget of SusCity. Therefore, neither the type of renovation system, nor the renovation rate, but the emission intensity of energy is the decisive factor. To be more precise, not only a radical transition to 1% of current emission intensity per kWh needs to be achieved until 2050, but also this transition needs to happen sooner rather than later, which becomes apparent when comparing the convex with the concave transition scenario. Only

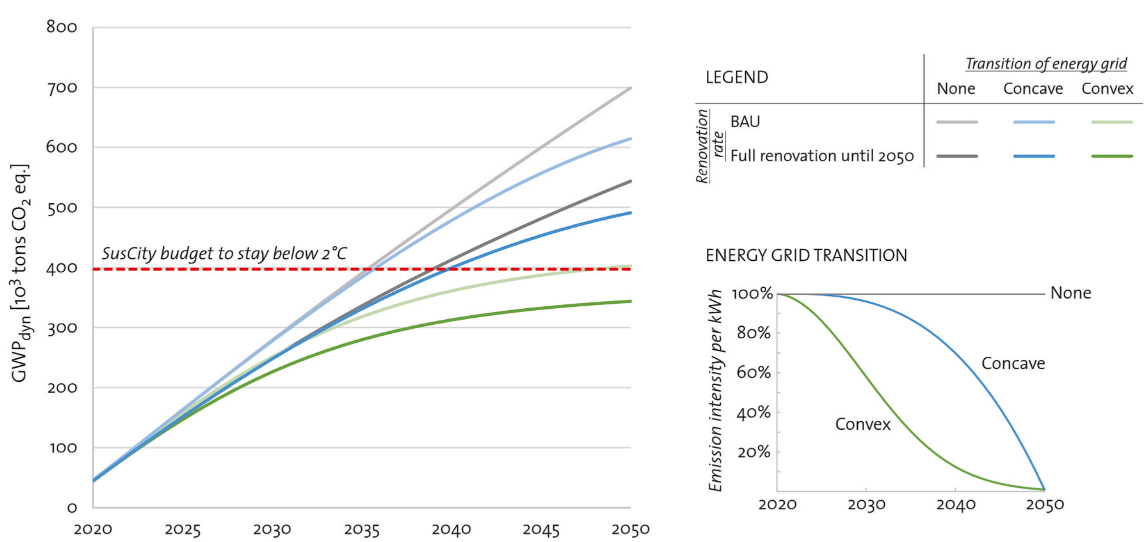


Fig. 7. Comparison of energy grid transition scenarios for GWP_{dyn} for the LC stages B4, B5 and B6 for the renovation of SusCity using the TES technology and a prioritized renovation strategy.

the convex energy grid scenario allows staying within the 2 °C budget of SusCity. This also implies that the remaining 2 °C budget will be needed for the energy transition. There is nothing left for building renovation. This emphasizes the need for carbon neutral and carbon negative materials, i.e. bio-based materials.

5.3. Limitations of the study

It needs to be noted that the present study is limited by the following aspects, which should be improved in future research:

- Only additional external thermal insulation for walls is analyzed. The other important components of deep renovation are not considered. Moreover, external thermal insulation is easier to apply but changes the appearance of external façades, which can be an obstacle when renovating historic buildings. For such buildings, an internal insulation is the only option but reduces the wall's hygrothermal performance. Claude et al. [78] found that bio-based insulation enables a better hygrothermal performance than other conventional materials. Therefore, even for internal insulation, bio-based materials are a promising material choice;
- This study excludes an economic analysis. Future research should analyze the financial feasibility and potential barriers of adapting non-conventional material solutions for energy retrofitting and achieving the suggested ambitious renovation rate of 3.3%;
- This study excludes dynamic thermal simulations, which can provide important insights into the different performance of bio-based materials and should be further studied. Fu et al. [79], for example, examined the thermal performance and hygrothermal behavior and found that ICB, in comparison to pine boards, can absorb more heat. Moreover, they found that the overall moisture content of a building with ICB is lower.
- Only the 2159 dwellings out of the 3259 buildings in SusCity were considered. The difficulty in obtaining data for non-residential buildings is the reason why they were not included in this analysis;
- Every dwelling was assigned to an archetype meaning that some buildings could vary significantly from the assumed generalizations;
- No sensitivity analysis for LC stage B6 was performed. Yet, Silvestre et al. [58] showed that different scenarios (e.g. lower occupation, home office) can significantly impact the operational energy needs;
- The downscaling of the global carbon budget to building renovation of SusCity is highly uncertain because of the small scale of the SusCity case study. Moreover, only external thermal insulation and operational energy use is studied but no designated carbon budget for these activities exist. In addition, some argue that using economic power instead of population size enables a fairer distribution of the total budget [62].

6. Conclusions

A novel methodology was proposed and tested for an urban area in Lisbon, coupling dynamic MFA with DLCA, to analyze the thermal retrofit of dwellings. In this way, the strengths of a bottom-up building stock model were combined with the accuracy of a DLCA that considers the timing of emissions and biogenic carbon uptake. Therefore, it allows defining renovation strategies considering the dynamics of urban-scale renovation and the interaction with the natural system. The bottom-up building stock model allows to group similar buildings and to identify those with the highest needs. However, the significance of such a prioritization strategy is dependent on the current performance of buildings with a higher varying and older building stock likely benefitting more from such a strategy.

Moreover, this study confirmed that:

- bio-based renovation systems offer the additional benefit of carbon uptake compared to conventional systems and they allow to reduce the total impacts arising during LC stages B4 and B5;
- the more biomass, the better (TES uses straw as insulation and timber for the structure and was therefore more beneficial than ETICS with ICB that only uses cork as insulation);
- the use of biomass from fast-growing plants is better suited for climate change mitigation until 2050 than slow-growing materials (straw allows to achieve a negative GWP faster than cork), but in the long-term (200 years horizon) the differences between fast- and slow-growing biomaterials level out.

Finally yet importantly, an analysis at the urban scale, in contrast to the building scale, provides a more accurate view of the relation between embodied and operational energy because it considers already renovated and non-renovated buildings. It can be recommended to consider the age and constitution of a building stock when formulating renovation strategies, meaning to prioritize the renovation of poorly thermal insulated buildings. A scenario analysis of the emission intensity of supplied energy suggests that only a fast and drastic transition of the energy grid could enable to comply with a carbon budget that keeps global warming below 2 °C.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.107773.

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